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ABSTRACT

Water heating accounts for the second largest portion of residential building energy consumption, after space conditioning. Existing HPWH products are a technical success, with demonstrated energy savings of 50% or more compared with standard electric resistance water heaters. However, current HPWHs available on the market cost an average of $1000 or more, which is too expensive for significant market penetration. What is needed is a method to reduce the first cost of HPWHs, so that the payback period can be reduced to a period short enough for the market to accept this technology.

A second problem with most existing HPWH products is the reliability issue associated with the pump and water loop needed to circulate cool water from the storage tank to the HPWH condenser. Existing integral HPWHs have the condenser wrapped around the water tank and thus avoid the pump and circulation issues but require a relatively complex and expensive manufacturing process. A more straightforward potentially less costly approach to the integral, single package HPWH design is to insert the condenser directly into the storage tank, or immersed direct heat exchanger (IDX).

Initial development of an IDX HPWH met technical performance goals, achieving measured efficiencies or energy factors (EF) in excess of 1.79. In comparison conventional electric water heaters (EWH) have EFs of about 0.9. However, the initial approach required a 2.5" hole on top of the tank for insertion of the condenser – much larger than the standard openings typically provided. Interactions with water heater manufacturers indicated that the non standard hole size would likely lead to increased manufacturing costs (at least initially) and largely eliminate any cost advantage of the IDX approach. Recently we have been evaluating an approach to allow use of a standard tank hole size for insertion of the IDX condenser. Laboratory tests of a prototype have yielded an EF of 2.02.

1. INTRODUCTION

Water heating accounts for about 4% of all the energy used in the USA and 10% of all energy used in buildings - a total of about 3.8 quadrillion Btus, or quads (4.0 exajoules) (DOE/EERE 2005). Consequently, improving the efficiency of water heating can play a significant role in reducing the nation's thirst for energy. The efficiency of electric resistance water heaters (EWH) has just about topped out, and the efficiency market is tightly compressed. US efficiency standards require EWHs to have a minimum Energy Factor (EF, standard water heater efficiency metric) of 0.90, and the most efficient models have EFs of about 0.94 to 0.95. There is simply not much room left for further improvement in EWH efficiency. The heat pump water heater (HPWH) however can overcome this limitation and increase electric water heating efficiency by a factor of two or more.

There are two basic designs of electric HPWHs – add-on and integral. The “add-on” type contains a compressor, evaporator, controls, and a water-cooled condenser and is installed in conjunction with an existing EWH. This type includes a small pump to circulate water from the EWH tank to the HPWH. Piping must be installed between the EWH and HPWH, and the HPWH generally replaces the function of the lower electric resistance element in the EWH. An advantage of the “add-on” type is that it can be retrofitted to existing EWHs. However installation of the interconnecting piping can be costly depending upon the situation and the circulation pump represents an added cost and reliability concern. Prices for current add-on models range from $900 to $1100 (uninstalled) (Ashdown et al 2004).

The “integral” type is a single package containing the HPWH components, controls, and storage tank. This design avoids the need for a water pump and associated piping. A cutaway view of an integral HPWH that was briefly introduced to the US market in 2003 (and since withdrawn due to low sales volume) is shown in Figure 1. This design was intended to target the large (>3 million units/y) replacement market for residential EWHs. The efficiency of this design was excellent with laboratory measured EFs of 2.2-2.4. Two intensive field test programs involving 38 units noted energy savings ranging from about 30% to >60% and diversified peak reductions of up to 1.9 kW in winter mornings and up to 0.6 kW in summer afternoons versus EWHs (Murphy and Tomlinson 2002; California Energy Commission (CEC) 2004). In addition, accelerated life tests indicated that the units should perform reliably for at least 10 years (Baxter and Linkous 2004). However, the average unit selling price was approximately $1200 (uninstalled). At this price level simple payback exceeded five years for the field test locations. The principal reason for the high cost was the effort needed to install the HPWH condenser coil on the storage tank. Results from the California field study indicate that if the integral unit installed cost could be reduced to $875 payback periods would range from 2 to 3 years in that state where electricity costs about 12 ¢/kWh on average (CEC 2004).

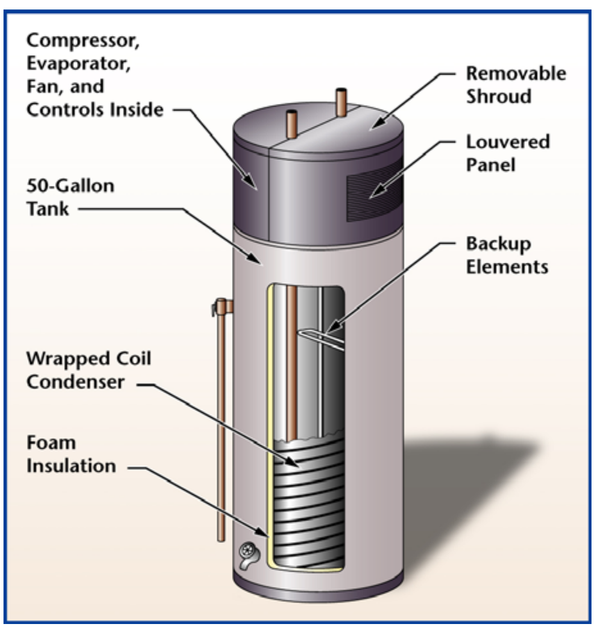

Figure 1: Cutaway schematic view of existing integral HPWH product (left side) and photo of tank with condenser installed (right side)

While current HPWH designs are technically sound and achieve impressive energy savings, their high first costs remain the most significant, though not the only, barrier to their wide market acceptance. Other barriers include lack of a network of competent and confident installers and the negative reliability history of previous (ca 1980s and 1990s) products. This paper discusses the development of two novel HPWH approaches that show promise to address the cost issue. A more straightforward potentially less costly approach to the integral, single package HPWH design is to insert the condenser directly into the storage tank, or immersed direct heat exchanger (IDX). This concept should reduce overall HPWH costs (hopefully to enable reaching an installed cost of $875 or less) because it eliminates any need for complex and costly assembly involving the water storage tank.

2. IDX SYSTEM DESCRIPTIONS

Two approaches to a low cost HPWH design based on the IDX concept have been developed. The first (see Fig. 2) involved a condenser design comprised of 2 “U-tube” circuits (four legs), each made from 3/8” (9.5 mm) copper tubing for a total of 48 ft^2 (4.46 m^2) of heat transfer area. The condenser design required that a special tank be made with a 2.5” (57 mm) threaded hole at the top so as to allow the condenser assembly to be inserted. Since conventional storage EWHs use 7/8” (22.2 mm) fittings, this represents a departure from standard EWH manufacturing. However, it was felt that with a large production volume the added cost of the larger fitting should be minimal. The compressor initially proposed for use with this IDX concept had a relatively large capacity (1-ton nominal) to reduce the need for backup electric resistance heating or eliminate it entirely.

The second approach is based on a condenser design that would enable use of the current standard tank fittings (see Figure 3). In this design a flexible linear condenser tube is inserted through a 7/8” (22.2 mm) hole on top of the tank using a bent sleeve through which the condenser tube is pushed. As the tube is pushed through the sleeve, it forms a helical coil. Figure 4 is a photo of a laboratory proof-of-concept prototype HPWH using this condenser design as installed in the testing chamber.

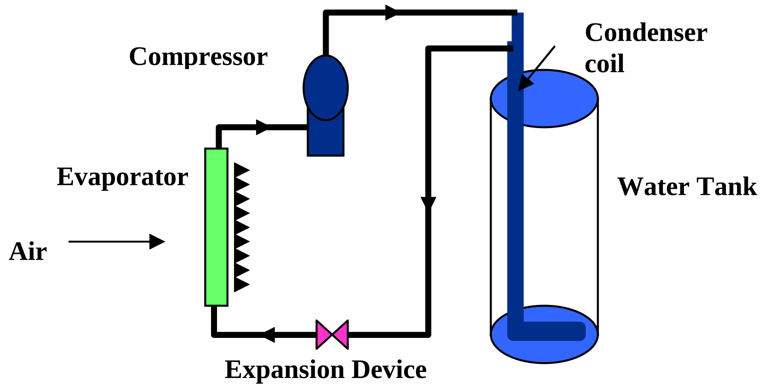

Figure 2: Original low cost HPWH design concept

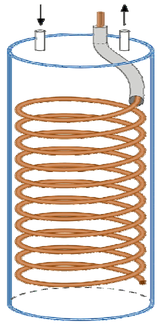

Figure 3: Coil design, 2nd IDX concept

Figure 4: Prototype IDX HPWH

The balance of the heat pump components for both concepts (compressor, evaporator, expansion valve, etc.) were mounted on top of the water heater tank as illustrated schematically in Figure 1 and shown in the photograph in Figure 4. Both systems used refrigerant R-134a as the working fluid.

3. SYSTEM PERFORMANCE – FIRST CONCEPT

Two prototype units for the first IDX HPWH concept were constructed for laboratory and field tests as part of a field demonstration of the immersed condenser design. Laboratory tests were conducted according to procedures outlined in the federal water heater test standard (Federal Register 1998). The tank was heated to a starting average water temperature of about 140°F (60°C), then six water draws of 10.77 gal (40.8 l) each were made at one hour intervals. After the 6 draws, the heat pump ran until the tank water temperature was recovered, or shut off by the thermostat on the tank.

The compressor initially specified for this concept had a relatively large capacity (1-ton or 3.5 kW nominal) to reduce the need for backup electric resistance heating or eliminate it entirely. However, lab performance with the large compressor was poor because the available immersed condenser area was insufficient resulting in excessive condensing temperatures. It was replaced on the second prototype with a 4,000 Btu/h (1.17 kW) refrigerator compressor. The prototype with the refrigerator compressor performed well, both for laboratory testing (EF=1.79) and field testing (average COP=1.75). Field test results from this unit are summarized in Figure 5.

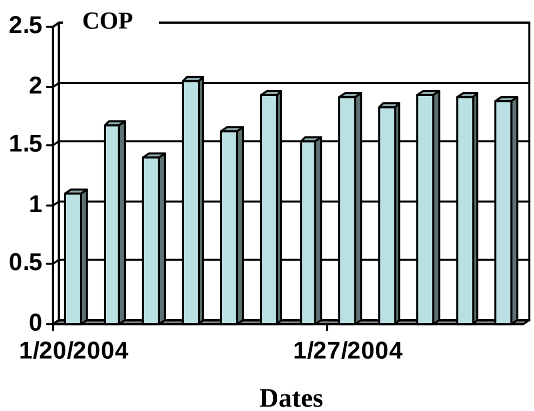

Figure 5: Field test data of first IDX HPWH prototype

Although cost estimates exclusive of the tank showed that the assembled IDX HPWH should cost $150, the fact that it required non-standard tank fittings was problematic from the standpoint of added cost and lack of interest by water heater tank manufacturers. However, the work did suggest that if there were a simple way to install an immersed condenser with sufficient surface area into a conventional insulated electric storage water heater, significant cost reduction could be achieved through use of standard mass produced tanks.

4. SYSTEM PERFORMANCE – SECOND CONCEPT

In 2005, work was completed on the initial laboratory development and testing of the second IDX condenser design. A double wall tube was formed with ½" (12.7 mm) and 7/16" (11.1 mm) copper tubing. However we found that the coil forming process, which included hydraulically expanding the inner tube to form a firm bond with the outer tube, work hardened the double wall tube, making it difficult to insert into the tank without kinking or crushing. Softening (annealing) the hardened double wall tube will solve the problem, but requires heating the tube to 1000°F (538°C) and then allowing it to cool down slowly (Mei, 2005). Equipment such as induction heating systems may be successfully used for this purpose, but the project schedule and resource constraints dictated that we use a single-wall condenser for this initial proof-of-concept laboratory testing.

From heat transfer tests we determined that the total heat transfer for a single tube (7/16" (11.1 mm) diameter) and the double wall tube were almost identical. While the single tube has a smaller heat transfer area than the double-walled tube, contact resistance between the inner and outer tubes of the double-wall design inhibits heat transfer. For the proof-of-concept testing, we inserted a single wall tube into the tank as shown in Figure 6, to experimentally study the heat transfer characteristics and energy efficiency that can be achieved with this new coil design. For the single wall condenser coil design, a ¼" (6.4 mm) diameter Teflon tube was selected as the inner tube to form a tube-in-tube heat exchanger. Teflon was selected for its flexibility and easy insertion. The Teflon tube is also very tough. It could withstand the pressure for heat pump application, and it can be used at high temperature (500°F or 260°C). When we completed the soldering of copper tubes together, with Teflon tube inside the copper tubing, the Teflon tube was then examined and found no trace of damage at all. Teflon is also an excellent insulating material. It will reduce the heat exchange between gas and liquid refrigerant (inlet and outlet of the condenser coil).

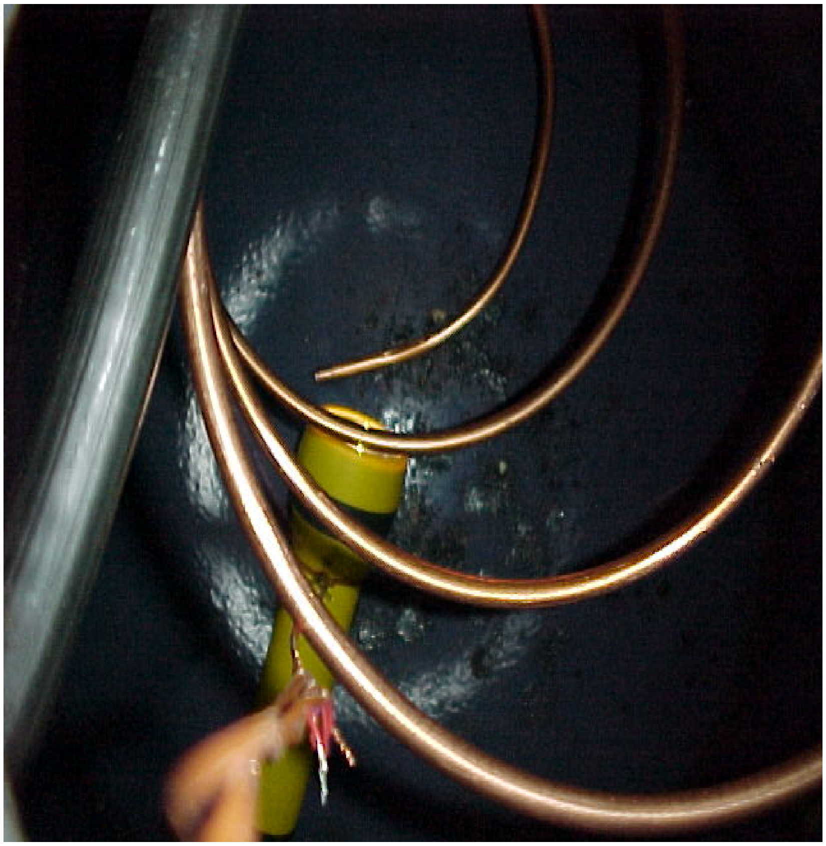

Figure 6: IDX condenser coil inserted into tank

Laboratory testing was conducted using the same procedure as for the first concept (Federal Register 1998). A nominal 66 gal (250 l) water tank with 3 inches (76 mm) of foam insulation was used for the test. After inserting a 70 ft condenser tube into the tank, it held 492 lb (223 kg) of water, or 58.97 gal (223.2 l). The tank was heated to a starting average water temperature of 140°F (60°C), then six water draws of 10.77 gal (40.8 l) each were made at one hour intervals. After the 6 draws, the heat pump ran until the tank water temperature was recovered, or shut off by the thermostat on the tank.

The tank water temperatures, total power consumption, and compressor suction and discharge pressures were recorded. Maximum compressor discharge pressure was 275 psia (1896 kPa), which is well within the safe compressor operating range. Figure 7 shows the power consumption and the average water temperature variation during the 24-h period. The figure indicates that the water at the top of the tank was never lower than 107°F (41.7°C) even after 6 draws. The water tank temperature was completely recovered after less than 8-h of heat pump operation. The heat pump was off for the remaining portion of the 24-h test.

Reduction of the test data revealed that the EF was 2.02, which is more than twice as efficient as conventional electric water heaters. This result was achieved using a single wall immersed condenser design for the proof-of-concept prototype HPWH. It is recognized that codes require that refrigerant-to-water heat exchangers in contact with potable water must be of a double-wall design. However, the test results show that the IDX concept is capable of yielding a HPWH design with reasonably high efficiency. The next phase of the work will focus on developing a workable double-wall condenser design.

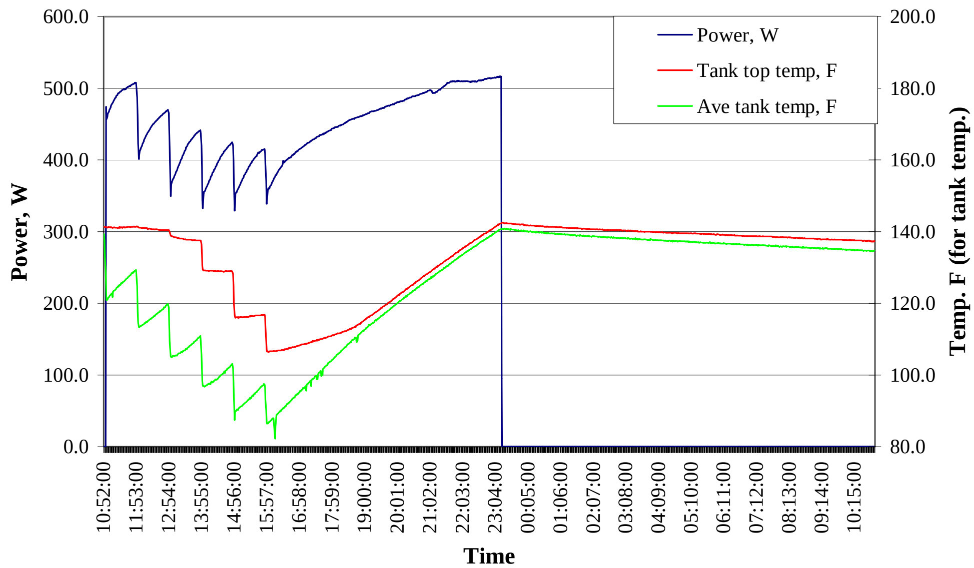

Figure 7: HPWH power consumption and tank water temperatures.

5. CONCLUSIONS

Two low cost HPWH designs based on the IDX condenser concept were developed and subjected to experimental evaluations. The initial concept achieved a laboratory measured EF of 1.79 and an average COP of 1.75 in a field test. It, however, required a modification of the standard water tank design to enable insertion of the IDX condenser into the tank. This was a problematic issue from the standpoint of added cost and lack of interest by water heater tank manufacturers. Therefore it was abandoned and a second design concept pursued that requires no modification of the tank. A laboratory proof-of-concept prototype HPWH based on the newer design achieved an energy factor of 2.02, 2.24 times higher than typical values for current electric water heaters (EF = 0.9). This result was achieved using a single wall immersed condenser design for the proof-of-concept lab tests. It is recognized that codes require that refrigerant-to-water heat exchangers in contact with potable water must be of a double-wall design. However, the test results show that the IDX concept is capable of yielding a HPWH design with reasonably high efficiency. The next phase of the work will focus on developing a workable double-wall condenser design and verifying HPWH performance with double wall condenser.

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